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This year has been characterized by major upgrades in facilities and equipment. In December of 1986, the first laboratories were moved into the new Electrical and Computer Engineering building. Laboratories associated with the Optoelectronics Research Center that are now operational in this new building include: the Class-100 cleanroom; two optoelectronics device physics laboratories - one devoted to relatively low power devices with experiments in nonlinear dynamics, static properties of multi-mirror cavities, narrow linewidth diode lasers, etc. and a second devoted to characterization of devices fabricated at the Center for High Technology Materials, and to high-power devices; a laser-materials interaction laboratory; laboratories for rf-sputtering of PLZT thin films; ion-assisted deposition of thin-films; materials characterization, bonding, e-beam evaporation; SEM facilities. Laboratories for ion-beam figuring and heterodyne characterization of high-speed uv-detectors, not funded as part of this program, have also been located in this facility.

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## 1. Introduction:

Very substantial progress has been made in the Optoelectronics Research Center program of the Center for High Technology Materials at the University of New Mexico during the course of this research grant.

This year has been characterized by major upgrades in facilities and equipment. In December of 1986, the first laboratories were moved into the new Electrical and Computer Engineering building. Laboratories associated with the Optoelectronics Research Center that are now operational in this new building include: the Class-100 cleanroom (see below); two optoelectronic device physics laboratories - one devoted to relatively low power devices with experiments in nonlinear dynamics, static properties of multi-mirror cavities, narrow linewidth diode lasers, etc. and a second devoted to characterization of devices fabricated at the Center for High Technology Materials, and to high-power devices; a laser-materials interaction laboratory; laboratories for rf-sputtering of PLZT thin films; ion-assisted deposition of thin-films; materials characterization, bonding, e-beam evaporation; SEM facilities. Laboratories for ion-beam figuring and heterodyne characterization of high-speed uv-detectors, not funded as part of this program, have also been located in this facility.

The Crystal Growth Facility on the South Campus has also been completed. The MOCVD reactor for the growth of atomically abrupt III-V semiconductor layers has been moved into this facility and has just completed initial growth runs. This is a world-class installation. The custom-designed reactor is certainly among the most capable system available and the facility and associated safety system are model installations.

It is convenient, although somewhat arbitrary, to subdivide the research program into materials, fabrication, and device categories. All of these programs are highly interactive and supportive and many of the research efforts of the Center for High Technology Materials involve aspects of all three areas. Coupled with these major areas are significant efforts in diagnostics, particularly laser spectroscopy, and in device analysis and modeling.

### 2.1 Materials Growth

As was mentioned above, the procurement and installation of the MOCVD reactor in the new Crystal Growth Facility has been completed during this reporting period. Only a few initial growth runs have been completed to date. Initial GaAs/AlGaAs growth runs, including 2.5-nm quantum wells, have displayed excellent photoluminescence and carrier mobility characteristics. For GaAs growth, state-of-the-art background carrier concentrations of  $\sim 2 \times 10^{14} \text{ cm}^{-3}$  have been achieved. Calibration runs and other characterizations are being carried out with the expectation of growing graded index - separate confinement heterostructure (GRIN-SCH) laser structures early next year.

The liquid-phase epitaxy (LPE) system has been moved into the class-100 cleanroom area. LPE has complementary growth characteristics to MOCVD which are important for many complex device structures. Work is underway at improving the vacuum system with the immediate goal of growing double-heterostructure diode lasers.

Carrier recombination and trapping at GaAs/air interfaces are significant limiting mechanisms for a wide variety of electronic and optoelectronic devices fabricated from GaAs. Better understanding of these effects, and more effective surface passivation

techniques would significantly impact the potential applications of these devices. A systematic study of the laser-induced degradation of the photoluminescence (PL) efficiency from GaAs surfaces under a variety of conditions has been carried out. For the first time, two regimes were observed in the degradation of the PL from freshly cleaved GaAs (110) surfaces. A fast decay occurring in 1-2 seconds independent of the laser illumination and a much slower, power-dependent, decay observed in all samples including n-type, p-type, Cr-doped and liquid-encapsulated Czochralski (LEC) material. The time dependence of this slower decay was fit to a simple, universal power law expression. (Also partially supported by AFOSR Contract #AFOSR-86-0120)

A rf-sputtering system for the growth of lead-lanthanum-zirconate-titanate (PLZT) films has been brought up during this reporting period. PLZT is a nonlinear optical material that will be used for thin-film and waveguide nonlinear devices. Japanese researchers have reported high-speed switching (3 GHz) in PLZT waveguide total-internal reflection switches. PLT 28/0/100 films of thicknesses up to 2.5  $\mu\text{m}$  have been deposited on various substrates including fused silica, Si(100) and  $\text{Al}_2\text{O}_3$  (0001). Films with amorphous, polycrystalline, or highly oriented crystal structures have been obtained, depending on the deposition conditions. The properties of these films have been investigated using x-ray diffraction, scanning electron microscopy and energy dispersive x-ray analysis. A water-cooled magnetron source has been installed to upgrade the system, resulting in significantly better film properties. Promising preliminary results have also been achieved with two additional systems: a four-target dc magnetron system which will provide much finer stoichiometry control and the exciting possibility of layered structures, and an ion-assisted, ion-beam deposition system. This last is the first such system applied to the deposition of PLZT and offers the potential of lower substrate temperatures which are more compatible with GaAs substrates while at the same time offering denser films and higher quality surfaces.

## 2.2 Fabrication and Processing

As was discussed in the introduction, the 2,000 sq. ft. class-100 cleanroom in the new EECE building has been brought to operational status. Seven of the eight cleanroom bays are now operating; these are organized as follows:

- photolithography (ovens, spinners, 0.75- $\mu\text{m}$  deep-uv mask aligner)
- thermal processes (diffusion furnaces, rapid-thermal anneal,  
photochemical photoresist stripper, alloy station)
- deposition processes (LPE reactor, low-pressure chemical vapor deposition  
system)
- wet chemistry (2 bays, chemical hoods, acid baths, cleaning stations, etc.)
- dry-etching processes (reactive-ion etch, reactive-ion beam etch)
- characterization (stylus profilometer, microscopes, probe stations,  
computerized ellipsometer)

In addition, an e-beam metal evaporator, substrate polisher and thinner, wire-bonder, scribe/cleaver, and die-bonder have been installed and are operational outside of the cleanroom area. Materials characterization facilities include low-temperature photoluminescence, Hall and magnetoresistance probes, and an electrochemical profiler to provide carrier concentration vs. depth profiles. Additional device characterization equipment includes computerized C-V and I-V curve tracers, and a network analyzer extending to 4 GHz.

These facilities have now reached the point where multilevel processes are being

carried out and devices are being fabricated. Both diode laser structures and high-speed detectors have been fabricated. Considerable efforts have also gone into facilitating the clean room over the past year. A liquid nitrogen tank has been installed in the receiving area, the  $N_2$  boil-off being provided to all laboratories as a clean, dry compressed gas source. A deionized water system has also been installed.

Submicrometer gratings are essential parts of many optoelectronic and integrated optical devices. Gratings are used to couple free-space radiation to waveguide and diode laser modes and as reflectors for integrated distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers. We have explored the use of fabrication techniques based on holographic photolithography to fabricate these structures with a particular emphasis on limits to aspect (width/depth) ratios. Holographic gratings with periods as small as 700 nm, rectangular profiles with linewidths of less than 120 nm, and depths of 1.2  $\mu\text{m}$  (aspect ratio of 10:1) have been formed using positive photoresist on Si substrates and visible laser exposure (488 nm). Similar aspect ratios have been achieved at a 400-nm period using 334-nm exposing radiation. A simple exposure and development model which accounts for these large aspect ratios and predicts the grating fabrication limits has been developed. These aspect ratios are significantly higher than any previously reported. Experiments aimed at studying optical coupling into semiconductor materials and thin-film waveguides using these gratings are underway. (This work was also partially supported by AFOSR Contract #AFOSR-86-0120.)

### 2.3 Devices

Propagation of electromagnetic waves in multiwaveguide structures can be described in terms of a coupled mode theory. The guided modes in such a system (supermodes) are represented as a linear combination of the modes of individual waveguides constituting the structure. An improved coupled mode theory, partially developed at CHTM, takes account of coupling between all participating waveguides, not just the nearest neighbors as in the conventional approach, and treats properly the power conservation by including interference terms involving fields from all pairs of waveguides. It was pointed out recently that numerical results similar to those from the improved coupled mode theory are obtained from a variational principle, but a number of differences seemed to exist between the two theories. This led to a reformulation of the improved coupled mode theory that has the merit of being simpler while rendering results marginally better than the previous formulation. The simple, conventional theory gives incorrect results even in the very weak coupling limit, hence the improved theory must be used in order to ensure that the solutions are accurate.

The improved coupled mode theory referred to above dealt with coupled waveguide systems in which each individual isolated waveguide supports only a single guided mode. In many practical situations, however, the individual waveguides support two or more such modes. For these applications the improved coupled mode theory has been extended to the case of coupling among multimode waveguides and generalized to include also anisotropic media. Theoretical research is aimed at predicting properties of strongly index-guided phased-array lasers. These predictions are going to be verified by fabricating and characterizing properly designed devices.

Many optoelectronic devices, such as directional couplers, modulators, switches and Y-junction phase-coupled laser arrays, contain sections with non-parallel waveguides. The influence of these sections was usually ignored in the coupled-mode type of analysis which was limited to parallel waveguides. Hence, an extension of existing theory to systems of non-parallel waveguides is needed. The improved coupled-mode theory has been

generalized to describe approximately the coupling among tilted waveguides. This is achieved by slowly varying the waveguide separation. The new formulation is found to have significant bearing on the design of directional couplers and is expected to be useful in the analysis of Y-junction phased arrays.

In general, index-guided phased array semiconductor lasers with  $N$  coupled single-mode waveguides may lase in any of  $N$  supermodes (or array modes). Much attention has been devoted to fabricating arrays favoring the lowest-order supermode, the only one with a single-lobe radiation pattern. Of even greater importance is the problem of stabilizing whichever mode the array selects, since one may then design and implement a suitable optical system to utilize the output beam. The primary reason for supermode instability above threshold is the incomplete utilization of the injected carriers with increased pumping. A new design of phased array lasers that overcomes the stability problem ensures that the supermode of interest has an equal-amplitude envelope over the entire array except for the two outermost stripes. Efforts to manufacture phased array lasers conforming to the new design are currently under way, in cooperation with Wright-Patterson Air Force Avionics Laboratory. A mask set for photolithographic fabrication of multistripe devices has been designed and the masks procured. Fabrication will be carried out both at CHTM and at the Air Force Avionics Laboratory. Devices will be analyzed at CHTM and at Kirtland AFWL.

Conventional phased array lasers with uniformly distributed identical waveguides favor the highest-order supermode that emits a twin-lobe radiation pattern. This is undesirable in most applications and considerable effort has been put on development of more sophisticated structures that would favor the lowest-order supermode radiating in a single-lobe. Chirped arrays have been considered in search of a design that might result in stable, lowest-supermode operation. By varying the width of waveguides and spacings between them one can alter the relative thresholds of individual supermodes. Another important element of the design is to allow for excess gain to be present in interspaces between the guides, as this alters considerably the order of excitation of supermodes. A detailed study of a number of designs of index-guided chirped arrays has been performed, including linearly chirped arrays, arrays with triangular chirping, arrays with saw-tooth chirping, and various designs of arrays with simultaneously varying emitter width and spacing. A common problem with large arrays is the relatively poor mode discrimination. This can be remedied by proper gain tailoring, which results in significantly higher gain for the lowest-order supermode. Further improvement can be achieved by cutting off the highest-order supermodes, thus reducing mode competition due to spatial hole burning effects above threshold. This work, carried out in cooperation with Wright-Patterson AFB, will lead to development of prototypes of some of these designs. Simultaneous fabrication effort is carried out at CHTM Crystal Growth Facility.

The linewidth broadening factor, describing the coupling between carrier-concentration-induced variations of real and imaginary parts of susceptibility, is one of fundamental parameters for semiconductor lasers. Following a thorough and critical review of topics related to the linewidth broadening factor, prepared as an invited paper for IEEE Journal of Quantum Electronics, a research program has been established. Initial effort concentrates on the analysis of transient behavior of diode lasers including the effects of nonlinear gain. Several experimental techniques are envisaged to measure the linewidth broadening factor, including external-cavity coupling and injection locking.

There is a great deal of current interest in instabilities and chaos in nonlinear optical systems. Semiconductor lasers are particularly appropriate vehicles for studies of these effects owing to their large nonlinearities due to the strong dependence of refractive index on carrier density. Also, because of the wide-ranging applications of these lasers,

understanding their nonlinear dynamics is essential. External feedback can exert a dramatic effect on the output power, coherence and stability of semiconductor lasers. Most examples of complex instabilities in semiconductor lasers have been studied in external-cavity configurations, often with deliberate asymmetries such as tilted external mirrors. The effects of such procedures have not been previously investigated and are not well understood. A systematic experimental and theoretical study of the effects of small asymmetries induced by external mirror misalignment on the properties of external-cavity semiconductor lasers has been undertaken. The results demonstrate that, in addition to the length and coupling strength of an external cavity and the phase offset governing the interference between emitted and returning waves, the symmetry of the cavity alignment must be considered in determining the system properties, especially the noise and modulation response. We have observed and explained undulations in power as a function of mirror tilt as well as regimes in which complex noise spectra occur. It is important to study the characteristics of tilted external resonators to allow for the effects of misalignment in real situations, and to understand the processes whereby tilting is used in combination with other stimuli to produce complex and chaotic optical instabilities. Such instabilities should be avoided in most situations, but may find practical application as engineered nonlinearities in some systems.

### 3.0 Future Directions

The Optoelectronics Research Program at the Center for High Technology Materials has now assembled an outstanding set of experimental research facilities and personnel. Within the next year, it is anticipated that the MOCVD material will reach and exceed state-of-the-art capabilities in terms of carrier concentrations and mobilities, heterogeneous structures including quantum-well laser material and two-dimensional electron gas transistors (HEMTs) as well as modulators and improved high-speed detectors. An effort on surface-emitting lasers with integral heterostructure reflectors is also planned. The nonlinear optical thin-films effort will continue with extensive measurements of the optical properties of PLZT thin-films on both dielectric and semiconductor substrates. These developments will continue to be coupled to both laser spectroscopic efforts at analyzing the materials, fabrication processes and devices as well as strong, coupled experimental and analytical efforts in optoelectronic device design and characterization.

### 4.0 Journal Publications

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9. W. Streifer, M. Osinski, and A. Hardy, "A Critical Overview of Coupled Mode Theory (Invited Paper)," Proc. SPIE Vol. 835 - Integrated Optical Circuit Engineering V, SPIE Symposium on Fiber Optics and Integrated Optoelectronics, San Diego, California, August 17-20, 1987, pp. 178-187.
10. M. Y. A. Raja, S. R. J. Brueck, M. Osinski, and J. McInerney, "Laser-Induced Degradation of GaAs Photoluminescence," Applied Physics Letters 52, pp. 625-627 (February 1988).
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## 5.0 Conference Presentations

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2. M. Osinski and J. Buus, "Linewidth Broadening Factor in Semiconductor Lasers," Proceedings of the Tenth IEEE International Semiconductor Laser Conference, Kanazawa, Japan, October 14-17, 1986, pp. 40-41.
3. W. Streifer, M. Osinski, D. R. Scifres, D. F. Welch, and P. S. Cross, "New Design for Efficient, Stable-Supermode Phased-Array Lasers," Proceedings of the Tenth IEEE International Semiconductor Laser Conference, Kanazawa, Japan, October 14-17, 1986, pp. 78-79.
4. A. Hardy, M. Osinski, and W. Streifer, "Application of Coupled-Mode Theory to Nonparallel Sections of Directional Couplers," Technical Digest, OFC/IOOC '87 (Optical Fiber Communication Conference/Sixth International Conference on Integrated Optics and Optical Fiber Communication), Reno, Nevada, January 19-22, 1987, paper TUQ38, p. 132.



5. M. Osinski, W. Streifer, and A. Hardy, "Coupled-Mode Analysis of Chirped Phased-Array Semiconductor Lasers," Southwest Optics '87 Conference, Topical Meeting on Semiconductor Lasers, Albuquerque, New Mexico, February 10-12, 1987, Technical Digest Series Vol. 6, paper ThA6, pp. 168-171, Optical Society of America 1987.
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